Manufacture of Submarine Cable Repeaters and Ocean Block Equalizers

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In this article we describe the facilities and procedures used to manufacture SF repeaters and equalizers. Careful selection and training of production and inspection personnel play a vital role in achieving the desired standards in qualifying material and for assembly and test of units. Detailed engineering planning provides the best environmental conditions and manufacturing facilities and processes. Close collaboration by the manufacturer with Bell Telephone Laboratories during product design and specification and during manufacture assures a tightly controlled, well understood product.

I. INTRODUCTION AND OBJECTIVES

The responsibility for manufacture of SF Repeaters and the associated Ocean Block Equalizers is assigned to the Clark (New Jersey) Shop of the Western Electric Company. The organizational structure is comparable to those previously employed during manufacture of SB and SD Repeaters.[1,2] Nine levels of Laboratory Technicians perform work directly on the product.

Manufacturing development work on the SF Repeaters started early in 1963 and culminated in the first delivery of the finished product near the end of 1966. This and later experience proved that a practicable minimum of three years is required to (*i*) develop and procure facilities for the Clark Repeater Shop, (*ii*) obtain and qualify Laboratory Technicians, (*iii*) establish other Western and outside supplier sources for components, parts and material, (*iv*) manufacture (including six months of life testing) a set of apparatus, and (*v*) resolve design and manufacturing difficulties before the first repeater of new design is fully assembled

and qualified for project application. The sequence of major steps in repeater and equalizer manufacture is shown on Fig. 1.

Engineering and manufacture of SF Repeaters and Equalizers provided new challenges to Western Electric in production of high reliability apparatus. In order to achieve a broader band system, we had to employ not only new devices, with less-than-desired time-proven integrity, but also approximately twice the number of repeaters, com-

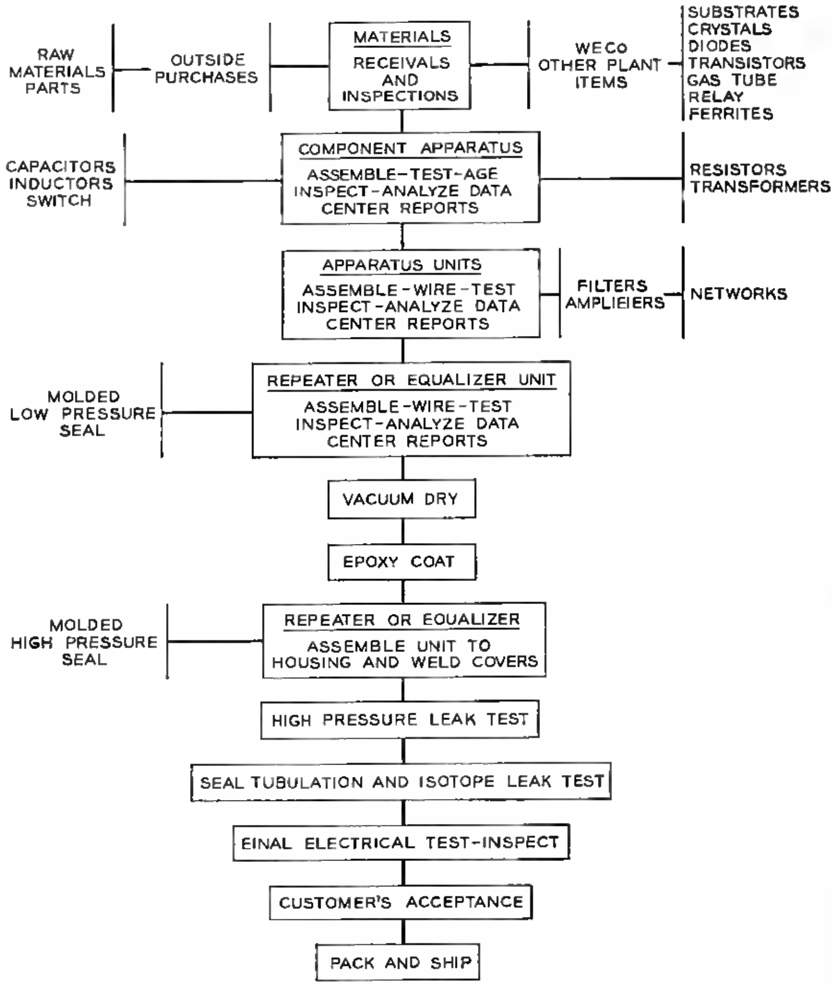

Fig. 1—Flow chart of major steps in the manufacture of repeaters and equalizers.

pared with SD Systems, in a given SF System to offset cable attenuation at the higher frequencies.

One essential key to success in manufacturing devices with exceptional reliability rests in the development and maintenance of a team with the integrity and dedication to strive constantly toward perfection and to be dissatisfied with less. By providing this prime essential, as well as superior environment and facilities, it is possible to realize the full reliability potential of the basic design.

1.1 *Production Objectives*

Although the initial production objective was to manufacture 417 SF Repeaters and Equalizers (sufficient for a Transatlantic System to be completed by the end of 1967), the program was revised downward to 152 units which were completed early in 1968. These units were provided for the Florida-St. Thomas System which was in service by August 1968.

After a production gap of about a year and a half, authorization was received to manufacture repeaters and equalizers for the TAT-5 System. To complete the units in time for an early 1970 in-service date, it became necessary to increase the manufacturing capacity to permit production at nearly double the previous peak rate. The Hillside (New Jersey) Shop (source of SB Repeaters) was reactivated by Western Electric Company as the Clark Annex. Operations temporarily transferred to this area included raw material inspection, inductor and transformer manufacture and directional filter section assembly work.

II. ENVIRONMENTAL CONTROL

"White" room conditions conform to an objective of less than 50,000 particles above 0.5 microns per cubic foot and temperature 75° ± 2°F. with relative humidity less than 40 percent. Humidity of less than 20 percent is maintained in the paper capacitor winding room. To monitor "dust" count effectively, we procured a Royco Particle Counter Model 200* and associated Royco Digital Recorder Model 122. This instrument permits identification and segregation of particles from 0.3 microns to 10 microns and larger. In case of difficulty, such information on particle sizes and concentrations can pinpoint the source of airborne contaminants.

Holding the environmental conditions to the desired levels during major moves and rearrangements and installation of new facilities was achieved through use of temporary dust-tight partitions, blocking

* Royco Instruments Inc., Menlo Park, California.

off registers to the air conditioning system and close examination of construction materials.

Laboratory Technicians wear special uniforms including caps and shoes. The uniforms and cleanliness rules are essentially those adopted for production of the SB and SD repeaters[1]. Pleasant working conditions and amenities contribute indirectly to reliability by keeping turnover low and morale high.

2.1 *Transportation of Project Apparatus*

The necessity for opening the Clark Annex introduced a new problem of transporting process project material between two locations. Heretofore component material from other locations (electron and gas tubes from the Western Electric plant in Allentown, Pennsylvania; transistors and diodes from the Reading, Pennsylvania, Plant; crystal units from Merrimack Valley, Massachusetts; relays from Burlington, North Carolina) were shipped fully encapsulated and required primarily shock and some temperature protection. Therefore, proper packing and transportation by messenger sufficed.

In the case of SF, airtight containers, as shown in Fig. 2, were used. After being loaded with the product, they are fastened to the floor of an air conditioned station wagon for transport. Shock monitors nested in each container provide control of apparatus against excessive shock or vibration. Test runs with an impactograph aided in route development.

III. PERSONNEL QUALIFICATION AND INDOCTRINATION

Manufacture of high reliability devices demands basic characteristics of integrity, dependability and meticulousness on the part of every employee. All Laboratory Technicians receive a 10-hour (five two-hour sessions) indoctrination course emphasizing the need to report the slightest deviation in their own work from established written requirements. The course covers in considerable (but nontechnical) detail the nature of the product and applications, the point at which each employee's effort fits into the whole, and general practices including use of uniforms.

3.1 *Qualification of Laboratory Technicians*

On-the-job training ordinarily takes two to four weeks, the time required before a Laboratory Technician is qualified to work on project material. The final test requires proving the ability to repetitively perform an operation faultlessly; for example, wind five paper capacitors

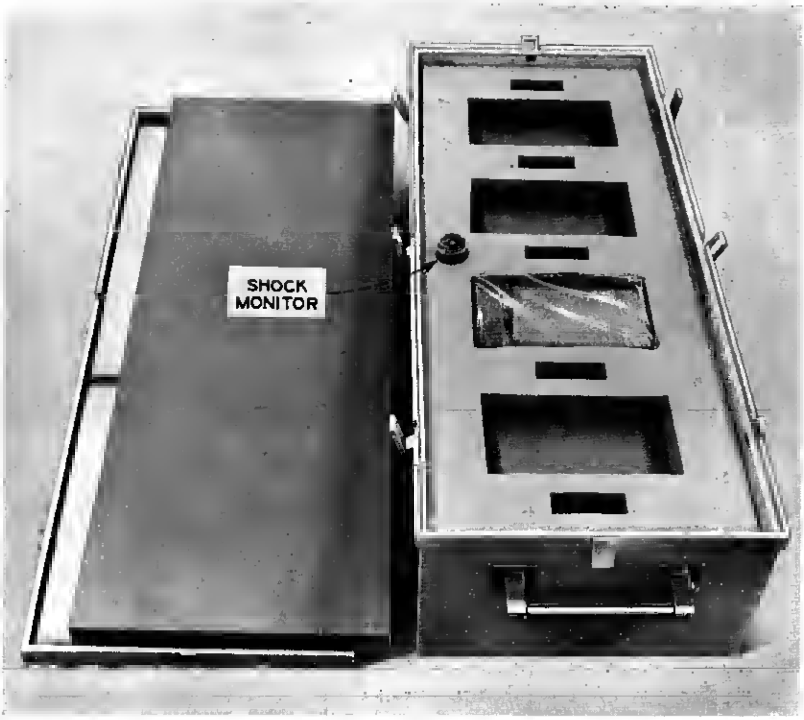

Fig. 2—Shipping container with product packaged and nested in plastic foam and protected by shock monitor.

in sequence perfectly. Only when an individual can demonstrate consistent mastery of all operations under his control by producing a predetermined number of pieces of required quality in a limited number of attempts can he be considered sufficiently qualified to work on project material. Furthermore, the Laboratory Technician is subjected to verbal interrogation to evaluate his understanding of the assignment. This inculcation procedure, though severe, is a basic prerequisite to built-in reliability. When a measurable deviation from what is acceptable (and within the control of the individual) is observed, the qualification procedure must be repeated. Individuals who fail to qualify as technicians are placed on other Company assignments without abasement. Disregard of requirements or taking short cuts for whatever reason can be very costly and is another basis for relieving a technician from submarine cable repeater work.

Modern training aids are used. Figure 3 shows an instructor using

Fig. 3—Dual microscope used to instruct a Laboratory Technician as to the quality of a soldered connection.

a dual microscope to instruct a technician on quality of a soldered connection by use of a dual microscope. For individual and group use, certain operations are video taped in black and white or color. Figure 4 shows a video taping session with a laboratory technician stacking a mica capacitor with the recording being monitored on the TV screen.

3.2 *Indoctrination of Support Personnel*

Equal care is exercised in the selection and indoctrination of new supervisors, engineers, production people, and so on. The thoroughness, accuracy and promptness of their activities has a prime bearing on the effectiveness of the laboratory technicians.

The purpose of and the need for conforming to the special Clark Shop practices is explained to all support personnel, accountants, guards, employment, cafeteria and yard help. The caliber and size of the janitorial force is particularly important in order to maintain environmental conditions.

Clark Shop personnel working in the period 1963–1970 proved that they were capable of developing facilities and introducing manufacture of a new design (SF Repeaters), maintaining production on the previous design (SD Repeaters), restarting an old design (SB Repeaters), and beginning production of a new design for the Government (SD-C Re-

peaters), without relinquishing high reliability in manufacturing standards. The results add to the assurance that methods for selecting, indoctrinating and qualifying laboratory technicians and for obtaining support personnel are proper.

IV. MANUFACTURING FACILITIES AND PRODUCT DEVELOPMENT

Over 7 million dollars were expended to provide new and changed facilities required for SF Repeater and Equalizer manufacture at the Clark Shop and for associated components made at other Western Electric manufacturing locations, primarily Reading and Allentown. These facilities were necessary to produce, age and test new apparatus components and assemblies, improve precision and increase manufacturing capacity.

The following illustrations show typical development work required to prepare for manufacture.

4.1 *Mica Capacitor Lamination Silver Coating Machine.*

More stringent electrical requirements dictated the need for better registration between silver coatings on the mica lamination. Increased output of the machine was required to meet schedule requirements.

Precise registration of the screens for transferring silver paste to

Fig. 4—Stacking of a mica capacitor being videotaped and viewed simultaneously on TV screen.

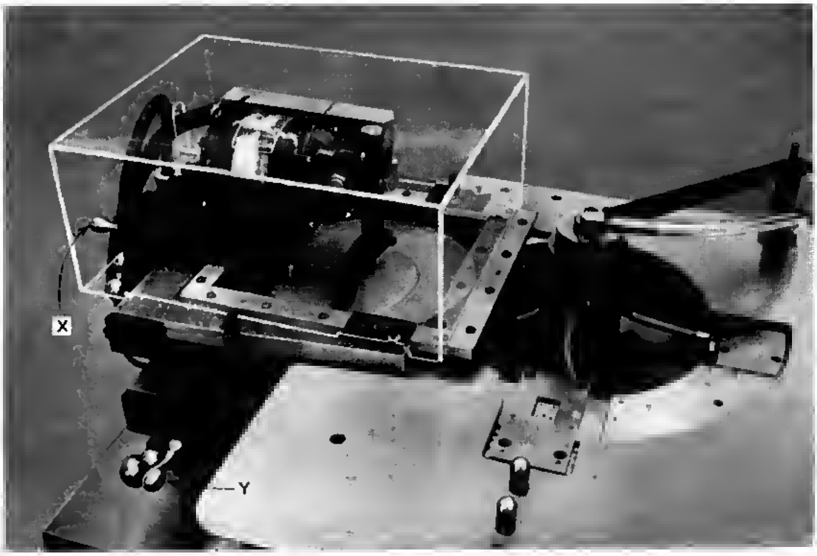

Fig. 5—Precision X and Y dimensional controls for Mica Silvering Machine are shown at left.

the mica lamination is achieved by the micrometer adjustments for X and Y dimensions on the silver coating machine shown in Fig. 5. The screens are made from 230 mesh stainless steel coated except for desired opening with polyvinyl chloride. Each screen is carefully inspected to avoid "petticoating" and to minimize possible variation in fringe capacitance. Consequently, by adding precision thickness sorting to the closely controlled registration, nearly every lamination can be stacked in a required mica capacitor.

4.2 *Central Conductor Mold for 3-Type Seal*

The techniques for molding the central conductor[3] which comprises a black oxidized phosphor bronze central conductor encapsulated in high density polyethylene are an important factor in assuring the integrity of the 3-type seal. Figure 6 shows the principal details of the mold. Before injection, the polyethylene and the metal conductor are heated to 260°C. (500°F.). Injection is at 2000 pounds per square inch, a pressure which is maintained up to three minutes. As cooling starts pressure is increased to 5000 p.s.i. and held while the polyethylene cools through its transition temperature of 110°C (228°F.). Pressure is then

reduced to 2000 p.s.i. and held until the molded part is completely cooled.

4.3 *Corona Noise Data Acquisition Test Set*

The repeaters in submarine cable systems are exposed to voltages sufficiently high to cause corona noise. Such corona causes interference with communications, especially data transmission, even though it is of a magnitude well below that which could cause physical damage or be observed visually.

It was possible to attain design objectives at reasonable facility cost by recording noise pulses above a threshold of a 31 microvolt peak signal during continuous high voltage dc exposure of at least 21 hours on all seals, power separation filters, repeater units and repeaters. Figure 7 shows a Laboratory Technician loading a seal for corona noise testing under water.

Product developments to minimize corona noise included prestressing of 3-type seals at approximately 7500 p.s.i. pressure and back-filling of repeaters with 50 p.s.i. of dry nitrogen.

4.4 *Celcon Plate Engraving*

One equalizer is ordinarily required for each ocean block of twenty repeaters. Therefore, the quantity of plates used in the cordword con-

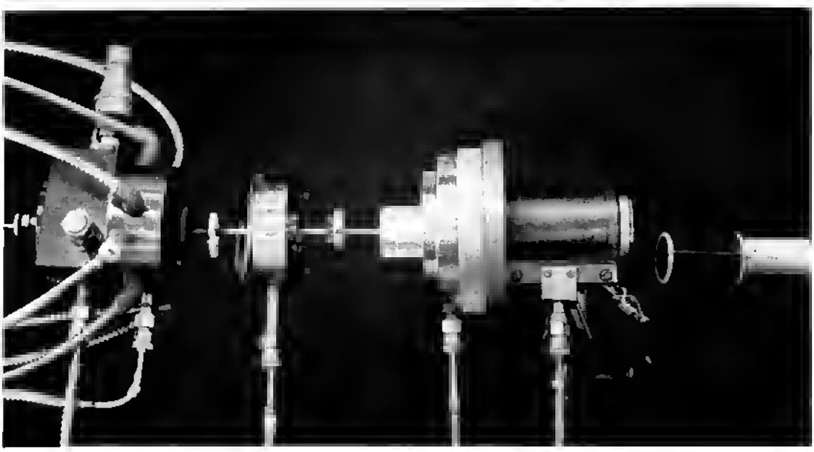

Fig. 6—3-Type Central Conductor Molding Tool. From left to right—Base with heating, cooling and thermocouple leads; central conductor and ceramic disc; vent ring and top mold plate; feeder plate; polyethylene slug extended from transfer tube with band heater; plunger with teflon "O" rings.

Fig. 7—3-Type Seals being inserted into water-filled cylindrical tubes for corona noise test.

struction[3] of equalizer networks is limited. Unless production exceeds 300-400 of a given plate, it is less expensive to machine the plate from Celcon* material rather than to build a mold, and mold the plates from the thermosetting diallyl phthalate used in repeater plates. Templates were made for the engraving machines together with insert templates for all the various holes and cavities for apparatus components. Consequently a very wide selection of plates can be engraved with a relatively small number of templates. Figure 8 shows an engraver with template and Celcon plate in position for machining and Fig. 9 shows Celcon plates before and after detailed machining.

4.5 *Engineering Developments on Product*

Engineering development work on the product, done in collaboration with the Bell Laboratories, is thorough, rigorous and uncompromising in the pursuit of high reliability. Sometimes this work leads to use of very different processes to achieve the manufactured item. To illustrate:

* Trademark of Celanese Corp. for their acetal copolymer plastic material.

Fig. 8—Engraver with template at right and celcon part at left.

4.5.1 *Adoption of Butt Brazing*

The central conductors of pigtails were joined to seals by a crimped ferrule. Air entrapment in the ferrule (a source of corona noise) made molding difficult and, as a result, product rejections were high. Butt brazing was proven-in but only after special procedures were devised to protect the plastic from metal splashes, filings, and so on.

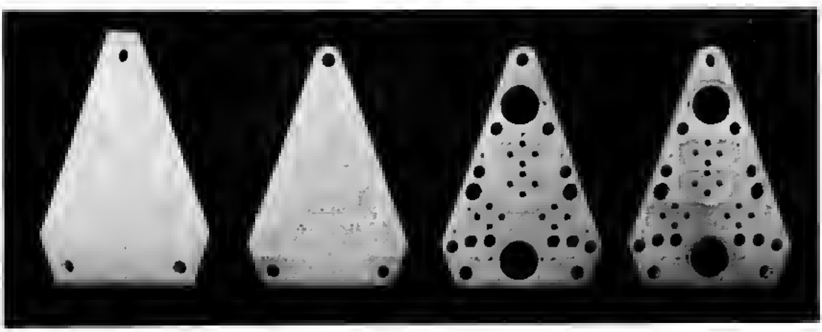

Fig. 9—Top and bottom celcon plates before and after engraving.

4.5.2 *Bolt Elimination*

Elimination of bolts as a design objective required the 3-type seal to be pressed into the covers, using a tin alloy gasket along with an O-ring. The alloy gasket is 95.5 percent tin, 3.5 percent silver and 1 percent cadmium. As the seal is pressed into position, the gasket flows into an annular cavity in the housing. This produces a hermetic fit which locks the seal into the cover. Also, tubulations have been changed to permit a press fit.

Improved X-ray inspection techniques were developed to control the quality of the tin alloy ring used to assure a tight pressed fit. A more recent development eliminates the press fitting by making the seal casing an integral part of the cover.

The remaining bolts were eliminated through use of a "major thread" threaded design for repeater and support housings.

4.5.3 *Seal Modification*

In the early weeks of the Florida-Virgin Islands SF System, a few 3A seals leaked[3]. The improved 3C seal had already been designed, using a free-floating piston with 2000 pounds preload. Introduction of the new seal was expedited to equip a few repeaters of the Virgin Islands system and all TAT-5 repeaters.

V. NEW MATERIALS, APPARATUS COMPONENTS AND ELECTRICAL TESTS

Increasing the repeater band width from one to six megahertz in order to accommodate 800 instead of 136 simultaneous two-way conversations necessitated application of materials and electrical components new to undersea units. Significant component changes included transistors and diodes[4] for electron tubes, tantalum capacitors for paper capacitors and tantalum resistors for wire wound resistors. A new physically large low inductance capacitor was introduced (See Fig. 10). This capacitor is produced by foil wrapped externally on the epoxy coating of the repeater unit. Several types of components requiring long intervals to manufacture were made and stock-piled in numerous "post office" values to permit wide design choice at a late date for each tailor-made ocean block equalizer. Latch-type relays and a new, purchased selector switch were used in the equalizer.

Many of the major components in repeater manufacture are obtained from Western Electric locations: transistors and diodes from Reading; gas tubes and resistor substrates from Allentown; crystal units from Merrimack Valley; ferrites from Hawthorne, Illinois; relays from

Burlington, pigtail cable and braiding from Baltimore, Maryland; and thermistors from Kansas City, Missouri.

In view of the 6 MHz frequency, most components were necessarily of lower physical value than those used in SD Systems. Table I shows the value and accuracy ranges for apparatus used in SF Repeaters. Furthermore, precision test sets had to be developed with capabilities of measurements at frequencies as high as 500 MHz.

5.1 *Vendor Relationship*

Although many of the purchased materials and parts were similar to those used on the SD Repeater, in most cases new or modified tooling and gaging were required to assure conformance to specification. Gaps in production necessitated reestablishment and requalification of vendors, a tedious and costly procedure. Approved sources for new material were developed. Single lot material purchases were frequently resorted to in order to minimize variation; for example, a single large batch of polyethylene was procured to aid in uniformity of quality during seal

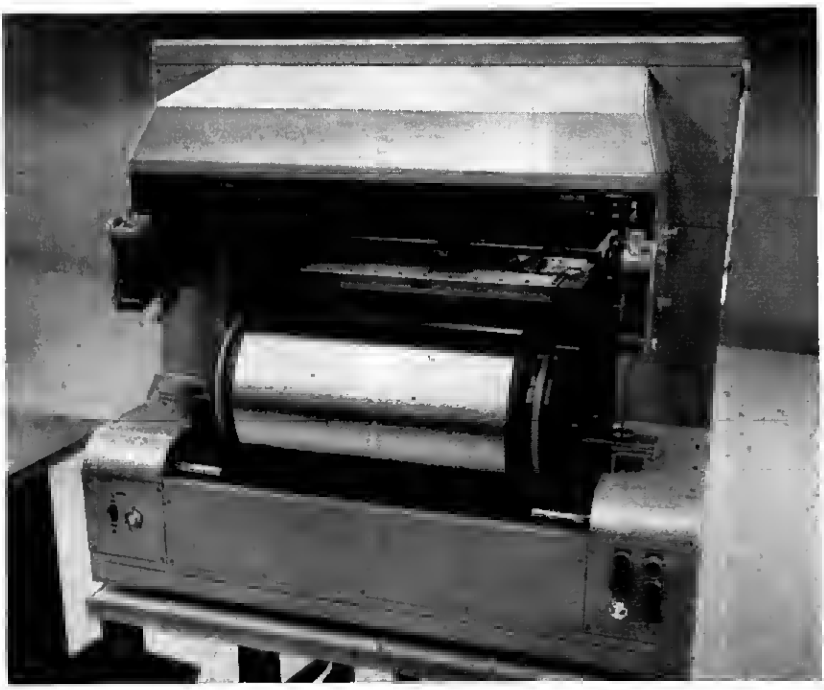

Fig. 10—Copper foil wrapped on epoxy coated repeater unit by machine.

TABLE I—APPARATUS USED IN SF REPEATERS AND EQUALIZERS

Part	No. of Different Codes	No. of Units per Repeater	No. of Units per Equalizer	Value Range	Accuracy Range
Capacitors					
High-voltage paper	2	2	3	0.02–0.18 μF	2–5%
Low-voltage paper	2	2	—	0.100–0.2200 μF	5%
Tantalum	4	16	—	1.0–10.0 μF	7%
Mica	136	46	131	9.96–9500 pF	0.25–5%
Inductors					
Air Core Solenoid					
Type-adjustable	60	21	55	0.227–139.0 μH	0.8–2.5%
Air Core solenoid type	87	10	80	0.087–1900 μH	0.5–15%
Transformers ferrite core	4	4	1	—	—
Resistors					
Tantalum	159	46	188	5.00–7000 ohms	0.5–5%
Bifilar wire wound	4	0	4	1.870–4.580 ohms	1.0–5%
Diodes	6	5	1		
Transistors	4	4	—		
Gas tubes	1	2	2		
Crystal	2	1	—		
Thermistor	1	1	—		

and pigtail manufacture, and a single lot of Celcon for equalizer plates was also procured. Engineering development work with material and parts suppliers is continuous. Comprehensive tests indicate whether each lot meets specifications. Variations are studied for pre-trouble drift or means of material improvement.

VI. CONTROL OF PRODUCT RELIABILITY

To remain competitive, broader band, more sophisticated systems must be made available with a high degree of reliability and at reasonable cost. To realize SF, transistors and resistors are essential. These items lack long-term performance history. There is also added risk due to many more repeaters being required for a higher frequency system (10 miles separation on SF System compared with 20 miles on SD Systems). Therefore, emphasis is added on the care with which the design is manufactured and tested.

The engineers translated the design into tools, fixtures, gages, test sets, ordering descriptions and detailed manufacturing layouts. All manufacturing facilities and procedures were subject to intensive check for conformance to requirement. Two pilot repeaters were made to prove that the design was manufacturable and that all tools performed as intended.

Laboratory Technicians are trained with non-conforming material. Product examiners patrol assembly operations and sample or detail product depending on the nature of the operation.

6.1 *Control of Deviations*

Whenever a deviation from the expected is detected, the deviating material must be set aside for detailed analysis. Product material and components are serialized which permits segregation and examination of the records to determine precisely what materials, processes and personnel were involved in the unit.

Stopping the job until the item is resolved generally is preferable to mating questionable material with other product material which might have to be discarded at a later, more costly stage. The questionable items number 100–150 per month and cause appreciable disruption in production flow. To assure that questionable items are dealt with properly and not eased through, work is controlled on a time rather than piece work basis. Many of the deviations are disposed of within a day or two; few take as long as a week to decide. Two or three Bell Laboratories designers are resident at the Clark Shop to review and evaluate observed variations.

Not all deviations involve possihle degradation of reliability. Frequently, an exceptionally good hatch of material is procured. Does the better material produce significantly better product? Could the supplier producc consistently to an upgraded specification?

6.2 *Control of Data*

Electrical test data on components, networks, amplifiers, repeater units and repeaters must be collected, recorded and analyzed particularly for trends. Not only do these trends forecast out-of-limit conditions in time to make necessary adjustments hut also they aid in evaluating the extent of equalization required for the repeaters during laying operations.

Most of the electrical data are transmitted directly to a Datex Receiver which produces cards for subsequent processing by an IBM 1620 Computer on a daily hasis[2,5]. In spite of excellent performance, certain improvements were desired (*i*) faster feedback, (*ii*) shared time, (*iii*) less handling and sorting of cards prior to printout.

(i) This episode showed the need for faster feedback:

(*a*) A *repeater unit* supervisory level tested out of limits.

(*b*) Next, analysis of earlier *supervisory oscillator* data showed heyond-3σ level deviation (hut in limits).

(*c*) Errant oscillator was replaced.

(*d*) A defective thermistor prohlem was revealed and corrected.

We could have avoided rework *c* and sped remedy *d* by faster data analysis and feedback.

(*ii*) Frequently special data and analyses bave been desired by Bell Laboratories and Clark Shop engineers to establish acceptahility of components deviating slightly in one parameter. Without shared-time capacity, the delay in performing such analyses diminished the value of the results and slowed the introduction of constructive action. Two examples are shown. First is Fig. 11, the Leakage Current for KS-19458, List 2, Tantalum Capacitors, and second, Fig. 12, the Insertion Gain of a series of repeater units. Botb printouts show nominal value, maximum and minimum limits, the actual average and 3 sigma deviations.

(*iii*) Extensive handling of punched cards bas been tbe practice. Data plotting of apparatus and network characteristics required transfer of primary data to compressed cards which in turn were processed to produce plotting cards which were then translated into a chart.

To provide the desired flexibility with adequate capacity, an IBM 1800 Computer has heen procured and installed. Tbe new system has a disc storage capacity capable of providing information on conformity

of transmitted data with apparatus requirements in a matter of seconds. The "On Line Printer" will print a record of each day's transmission for shop use without the extensive sorting and handling which cards previously required. Furthermore, the computer has a program which indicates priorities to operations to be performed upon receipt of data.

As valuable as the computer is, it does not perform the whole operation. It is so important that accurate data be transmitted and certain visual requirements be properly recorded, that product examiners do

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SER.	OP.18 RDG	OP.24 RDG	PRCT. DIFF.
74201	000460	000470	+002.174
74202	000440	000450	+002.273
74203	000380	000420	+010.526
74204	000430	000460	+006.977
74205	000410	000420	+002.439
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74207	000420	000460	+009.524
74208	000410	000450	+009.756
74209	000440	000450	+002.273
74210	000410	000460	+012.195
74211	000320	000390	+021.875
74212	000470	000510	+008.511
74213	000430	000460	+006.977
74214	000410	000430	+004.878
74215	000410	000450	+009.756
74216	000350	000430	+022.857
74217	000380	000420	+010.526
74218	000430	000450	+004.651
74219	000410	000440	+007.317
74220	000420	000440	+004.762
74221	000420	000480	+014.286
74222	000450	000460	+002.222
74223	000470	000460	-002.128
74224	000450	000450	+000.000
74225	000420	000430	+002.381
74301	000450	000430	-004.444
74302	000430	000430	+000.000
74303	000440	000440	+000.000
74304	000420	000430	+002.381
74305	000530	000460	-013.208
74306	000440	000460	+004.545
74307	000410	000420	+002.439
74308	000510	000530	+003.922
74309	000490	000460	-006.122
74310	000450	000480	+006.667
74311	000450	000460	+002.222
74312	000410	000460	+012.195
74313	000420	000450	+007.143
74314	000420	000460	+009.524
74315	000450	000460	+002.222
74316	000390	000410	+005.128
74317	000560	000520	-007.143
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74319	000390	000430	+010.256
74320	000380	000390	+002.632
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74325	000410	000420	+002.439

NO. OF PLOTS=50 AVG PRCT. CHANGE +005.697 -3 SIGMA -017.323 +3 SIGMA +028.717

Fig. 11—KS 19458, List 2, Tantalum Capacitor, Leakage Current.

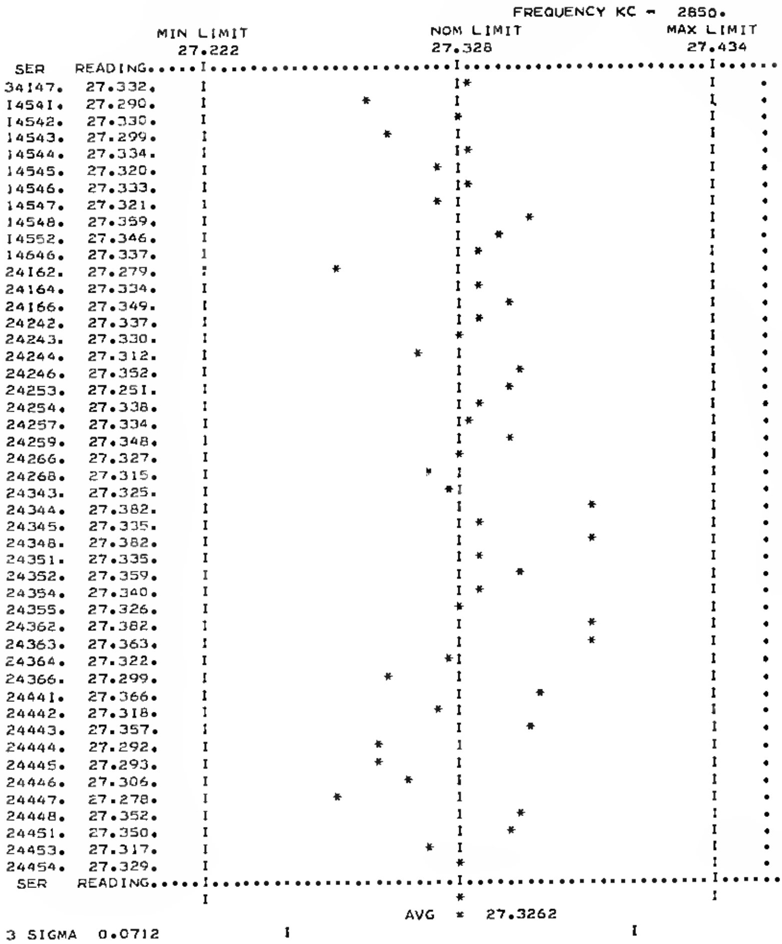

Fig. 12—304 AL Repeater Unit, Insertion Gain.

this process checking work, and in turn are subject to check by quality auditors. The auditors are responsible for all data being properly recorded and verified.

6.3 *Additional and Final Controls*

The Quality Assurance Organization independent from the Engineer of Manufacture prepares and carries out quality surveys in collaboration with their counterparts at Bell Laboratories. The surveys cover

in detail specific areas such as raw materials, paper capacitors, ground separation filters, and so on.

It might seem that controls to assure product reliability were extensive and expensive. This is true; however, not only must the "freaks" and "sports" be eliminated but also the minor mistakes made by human beings. Each step in the process of manufacture presupposes that all requirements have been met prior to the current step. If this is not so, the deviation may not be caught until a much more costly assembly has been made.

All final data is compiled by Western Electric in a mechanical and an electrical data book for each repeater and presented to the Bell Telephone Laboratories' representative who has been designated as the agent to accept each unit for the Long Lines Department of the American Telephone and Telegraph Company.

REFERENCES

1. Lamb, H. A., and Heffner, W. W., "Repeater Production for the North Atlantic Link," B.S.T.J., *36*, No. 1 (January 1957), pp. 103–138.
2. Johansson, S. G., "Manufacture of Rigid Repeaters and Ocean-Block Equalizers," B.S.T.J. *43*, No. 4 (July 1964), pp. 1275–1310.
3. Buus, R. G., Kassig, J. J., and Yeisley, P. A., "Repeater and Equalizer Design," B.S.T.J., this issue, pp. 631–661.
4. Wahl, A. J., McMahon, W., Lesh, N. G., and Thompson, W. J., "Transistors, Diodes and Components," B.S.T.J., this issue, pp. 683–698.
5. Tobey, S. B., "Semi-Automatic Data System," W. E. Engineer, *VII*, No. 1 (January 1963), pp. 12–16.